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Active carbody roll control in railway vehicles using hydraulic actuation

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ABSTRACT

Carbody tilting is used in railway vehicles to reduce the exposure of passengers to lateral acceleration in curves, allowing these to be negotiated at higher speeds with the same level of comfort. This, however, requires a rather complex actuation system that increases vehicle weight and reduces space for passengers.

This paper introduces a new concept that provides a limited amount of carbody tilt using hydraulic actuation. The device consists of interconnected hydraulic actuators attached to the carbody and bogies, replacing the passive anti-roll bar used in railway vehicles and in addition permitting active tilt control.

Three control strategies for the active hydraulic suspension are proposed, and the regulator gains are defined using Genetic Algorithm optimisation, based on numerical simulation of the running behaviour of the actuated railway vehicle in a high-speed curve. Finally, the performance of the actuated vehicle is assessed on the basis of numerical simulations, showing it is possible to increase significantly the vehicle's running speed in fast curves compared with a vehicle equipped with passive suspension.

1. Introduction

Recent decades have seen increasing integration of electronics and control into rail vehicles which used to be purely mechanical systems (Goodall, 2011). As part of this process, mechatronic technologies are increasingly being introduced in the running gear to improve running dynamics, service performance and ride quality (Bruni, Goodall, Mei, & Tsunashima, 2007; Goodall, Bruni, & Facchinetti, 2012).

In this regard, particularly noteworthy is the development of concepts for active secondary suspension (i.e. the suspension stage that isolates the carbody from the bogies (Goodall et al., 2012)), with the aim of raising service speeds on existing networks with the same level of ride comfort. Tilting carbody technology is an obvious example of this trend, but requires a rather complex bogie and suspension design based on a tilting bolster (Persson, Goodall, & Sasaki, 2009), which leads to increased vehicle weight and, given the constraints applied to the vehicle gauge, reduces the space available for passengers.

For these reasons, tilting body technology in the strict sense is not used for very high-speed trains, where severe constraints apply in terms of maximum axle load. For this specific application simpler and lighter carbody roll actuation systems have been proposed, aiming at permitting limited tilt angles (in the range of 1–2°, compared with the 6–8° maximum tilt angle achieved by tilting trains in the strict sense) that are nevertheless sufficient to increase service speed significantly on existing lines.

An example of this concept is the Japanese high-speed train Shinkansen Series N700, which attains approximately 1° tilting by actively controlling the pneumatic secondary suspension (Nakakura & Hayakawa, 2009; Tanifuji, Koizumi, & Shimamune, 2002). The same concept was proposed in Alfi, Bruni, Diana, Facchinetti, and Mazzola (2011), also showing the possible use of active roll actuation to reduce overturning risk in the presence of crosswind. Pneumatic actuation via secondary air springs is, however, not free from drawbacks: firstly, the actuation pass-band is limited, which may lead to delays in tracking the desired tilt reference. Secondly, the coupling of vertical and roll carbody motion and the dynamics of the pneumatic system cause disturbances affecting ride comfort and potentially leading to instability problems (Facchinetti, Di Gialleonardo, Resta, Bruni, & Brundisch, 2011; Tanifuji, Saito, Soma, Ishii, & Kajitani, 2009). Thirdly, with this actuation concept the use of a mechanical anti-roll bar cannot be avoided and the restoring roll torque generated by this component counteracts roll actuation, resulting in smaller tilt angles and increased energy consumption (Facchinetti et al., 2011).

This paper proposes an active anti-roll device to replace the passive anti-roll bar, making it possible actively to tilt the carbody.

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The use of an active anti-roll bar in rail vehicles was first suggested by Pearson, Goodall, and Pratt (1998), with a modified layout of a mechanical bar in which either linear actuators were introduced to replace the links to the carbody, or a rotary actuator was placed in series with the torsion bar. This original concept, however, is difficult to make fault tolerant, which is a major drawback. For this reason, in this paper hydraulic actuation is proposed instead, using cross-connected actuators so that a roll torque can be generated for a theoretically null vertical force: in this way it is easier to reject track irregularity related disturbances and, at the same time, tilt actuation becomes faster, more accurate and less energy consuming compared with pneumatic actuation. The hydraulic system can be dimensioned to provide the same roll stiffness as a conventional anti-roll bar when operated in the passive mode (Colombo, Di Gialleonardo, Facchinetti, & Bruni, 2013).

Three different control strategies are proposed for the active hydraulic anti-roll device and for all three control gains are defined based on Genetic Algorithm (GA) optimisation, having as multiple objectives the tracking of a reference carbody tilt angle, optimising ride comfort and keeping the energy required for actuation within acceptable limits. The reference tilt angle is defined on the basis of vehicle speed and curve geometry (curvature, cant, length of transitions), under the assumption that this information is made available to the control unit through geo-localisation of the train and mapping of the line, as implemented in the Shinkansen N700 train (Nakakura & Hayakawa, 2009). Other ways of defining the reference tilt angle, i.e. based on inertial sensors, would be possible and are in use, but it is not the purpose of this paper to investigate or discuss the benefits and drawbacks of alternative methods available to accomplish this task.

2. Concept of the active hydraulic anti-roll device

The active anti-roll device is designed to accomplish two main functions:

- actuate the desired carbody tilt angle when the vehicle negotiates a curve;
- provide the same carbody to bogie roll stiffness as a conventional anti-roll bar device when carbody tilt is not required.

A scheme of the device is shown in Fig. 1 for one bogie and includes the following main components:

- two linear hydraulic actuators AL and AR, placed at the left and right side of the bogie and connecting the bogie frame with the carbody;

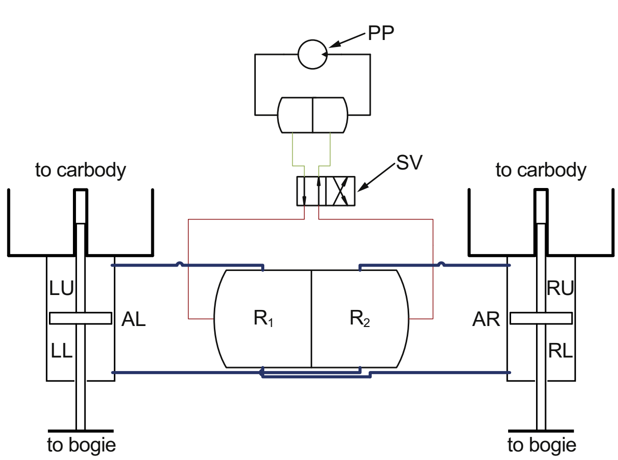

Fig. 1. Scheme of the hydraulic anti-roll device.

- a main hydraulic circuit (thick solid lines in the figure), cross-connecting the chambers of the actuators. Two reservoirs R1 and R2 are introduced in the circuit, and their volume is designed to provide the desired degree of roll compliance in passive mode;
- a hydraulic feeder circuit (thin solid line in the figure) to control fluid flow in the reservoirs with a pump (PP) and a servo-valve SV.

The working principle in passive mode is the same as for hydraulically interconnected suspensions developed mainly for automotive applications (Zhang, Smith, & Jeyakumaran, 2010). The upper chamber of the left actuator (LU) is connected to the lower chamber of the right actuator (RL) and the lower chamber of the left actuator (LL) with the upper chamber of the right actuator (RU). In this way, the hydraulic suspension nominally provides zero stiffness in the vertical direction and a non-zero roll stiffness.

A slow upward bouncing movement of the carbody will reduce the oil volume in the two upper chambers LU and RU and will increase the volume in the two lower chambers LL and RL by the same amount. Thanks to the cross-connection of the chambers, oil will flow from LU to RL and from RU to LL and, neglecting viscosity effects, no variation of the pressure in the chambers will occur. In a slow downward bouncing motion of the carbody, oil will flow from LL to RU and from RL to LU and again no pressure variation and hence no vertical force will be generated.

When instead the carbody performs a roll rotation with respect to the bogie for example counter-clockwise, the volumes in chambers LL and RU will decrease while those in LU and RL will increase. As a consequence, oil pressure will increase in LL and RU and decrease in LU and RL, producing a restoring moment in the roll direction.

The active roll function is only activated during curve negotiation and is implemented by the actuated servo-valve SV which controls the volume of oil in the two branches of the main hydraulic circuit, extending the linear actuator on one side while contracting the other actuator, thus providing carbody tilt. The reference carbody tilt angle is defined based on the cant deficiency of the curve which, in turn, depends on the curve geometry and on the vehicle speed. The position of the vehicle along the curve is assumed to be known from a positioning system, in the same way as in Nakakura and Hayakawa (2009).

The active hydraulic anti-roll device is used in conjunction with an active hydraulic secondary lateral suspension, whose function is to reduce the unloading of the inner wheels caused by the lateral displacement of the carbody and to prevent the lateral bump-stops to come in contact with the carbody, which would degrade ride quality. The active lateral suspension envisaged here is a simple “hold-off” type (Bruni et al., 2007), generating a lateral force in open loop which is defined to be proportional to the cant deficiency. Because of the simple control strategy envisaged for the active lateral suspension, the integration of active tilt and active lateral control at the secondary suspension as proposed in Zhou, Zolotas, and Goodall (2011) is not pursued here.

3. Mathematical model

A detailed non-linear model of the active hydraulic anti-roll device was derived and interfaced with a non-linear mechanical model of the entire rail vehicle, to optimise the controller parameters using the Genetic Algorithm and to assess numerically the performance of the actuated vehicle.